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Colluvium-filled Bedrock Depressions Formed around 10 ka in the Northern Part of Hiroshima Prefecture, Western Japan

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Abstract Many colluvium-filled bedrock depressions (CBDs) are observed on hillslopes in the northern part of Hiroshima Prefecture, western Japan. They can be divided into two categories based on the difference in color of the colluvium. One is judged to have formed in ca. 25 ka, while the other is probably in the Postglacial Stage. In four CBDs, which belong to the latter category but accumulate obviously thicker colluvium than most of other Postglacial ones, the basal ages of colluvium were estimated based on radiocarbon dating and tephrochronology.

The four CBDs simultaneously started to accumulate colluvium around 10 ka, in the Pleistocene-Holocene boundary. This simultaneity suggests a common climatic cause over the study area. This inception of accumulation must be related with the change in hydroenvironment. Although it is difficult to reconstruct paleoenvironment based on only the chronology of CBDs, the climate around 10 ka is expected to have been humid enough to cause gullying and landsliding close to the present channel head.

Key words: colluvium-filled bedrock depressions, paleoenvironment, hillslopes, Pleistocene-Holocene boundary, tephrochronology

1. Introduction

Hillslopes in mountainous areas show irregular contour lines. Depressions lacking channels on hillslopes are called zero-order basins (Tsukamoto, 1973; 1974). Whereas the surrounding slopes are covered with only thin colluvium, the zero-order basins are generally mantled with thick colluvium, and some of them are filled up to the full so that they are not indicated by surface topography. Such buried depressions formed on bedrock are called colluvium-filled bedrock depressions (CBDs; Crozier *et al.*, 1990).

CBDs have been reported from many parts of the world (for example, Dietrich and Dorn, 1984; Mills, 1981; Meis and Moura, 1984; Botha *et al.*, 1994). In the west coast of North America, their development was discussed in reference to the climatic change

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since the Late Pleistocene (Reneau *et al*., 1986 ; Reneau *et al*., 1990). In Japan, Wako (1966), Higaki (1980), Takeshita (1987), Win Maung and Toyoshima (1989), Yoshinaga and Koiwa (1996), Yoshiki (1996a), and several others reported the basal ages of CBDs and discussed their formation. The basal age of colluvium indicates the inception of accumulation in the CBD, as well as the last erosion by gullying or landsliding there. If the basal ages of many CBDs cluster around a certain period, the erosion processes on hillslopes are considered to have been more active in the preceding than the following period up to present. Thus, based on the chronology of CBDs, the paleohydrological environment affecting slope development can be reconstructed.

This paper reports four CBDs, which formed in ca. 10 ka, Pleistocene-Holocene boundary, in mountainous region of the northern part of Hiroshima Prefecture, western Japan. The basal ages of the CBDs were estimated by radiocarbon dating (Locs. 1, 2, and 3) and tephrochronology (Loc. 4).

2. Study area

The study area is situated in the Chugoku Mountains, which lies east and west in western Honshu (Fig. 1). The altitude of the area ranges from 200 to 1,200 meters above sea level. The mountainous and hilly area has flat and accordant summit except the backbone range, although steep slopes, more than 40° and 100 to 400 meters in relative height, occur continuously on both sides of main rivers only. All of the CBDs reported in this paper are situated not on such steep slopes but on the low-relief areas at piedmont or accordant hilltop. The mean annual temperature and precipitation are 12.0°C and 1,495 mm, respectively, at Shobara, 16 km east-northeast of Miyoshi.

Large part of the study area is underlain by Mesozoic rhyolite, and the rest by Mesozoic granite and Miocene Bihoku Group comprising unconsolidated sedimentary rocks. The granite including granite porphyry are highly weathered near the ground surface.

Besides, this area is covered by several layers of eolian tephras which fell after the Late Pleistocene. The basal age of colluvium in Loc. 4 was estimated from the tephra stratigraphy.

3. Stratigraphy and chronology of CBDs

Many CBDs are observed on hillslopes of the study area. They can be divided into two broad categories on the basis of the difference in color of colluvium ; one is filled up with gravelly colluvium of which matrix consists of yellowish brown clayey loam or loamy clay, while the other is filled up or mantled with black soil or with

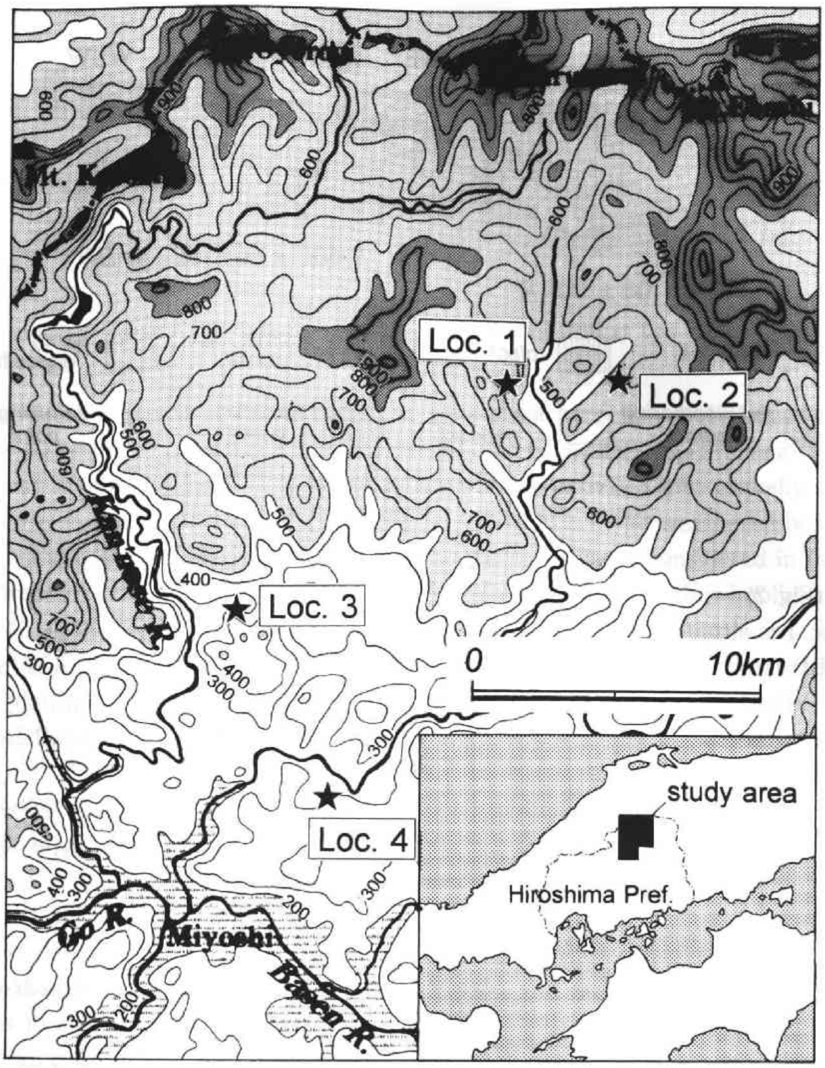

Fig. 1 Topography of the study area and location of the dated CBDs

gravelly colluvium of which matrix consists of brown or brownish black clayey loam. The former is regarded as a fossil CBD formed around 25 ka from the relationship between the AT tephra and the colluvium (Yoshiki, 1996b), while the latter is judged to have formed in the Postglacial Stage from the dark color of colluvium. The four CBDs described below belong to the latter category, although their colluvia are rather thick in comparison with other Postglacial ones, which are generally thinner.

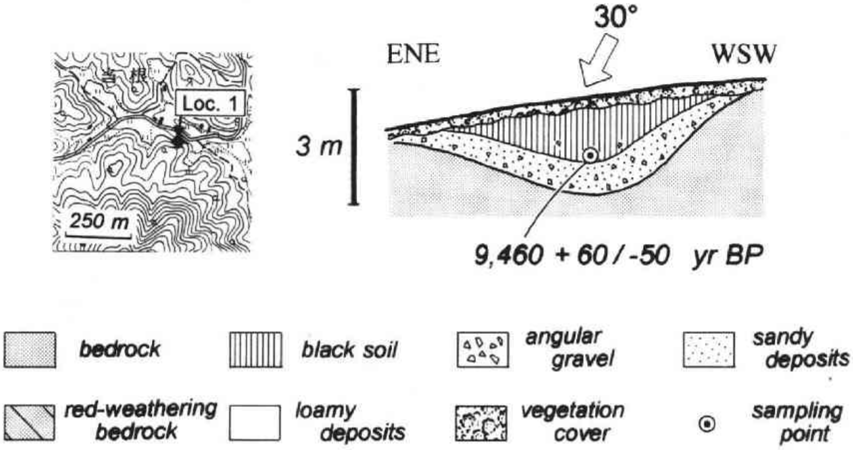

Fig. 2 Topography and a cross section of CBD at Loc. 1
Contor interval in the topographic map is 10 meters.

Loc. 1 (Fig. 2)

Loc. 1 is situated at the tail of densely-dissected erosional piedmont gentle slope. The CBD is on a valley-side slope whose inclination is an angle of 30° with a north aspect. The bedrock depression is fully buried so that the present topography shows no sign of the presence of the CBD. The granite bedrock is highly weathered into gravelly sand, which is a mixture of clay, coarse sand, and granule deriving from phenocrysts in granite. The outcrop surface, on which the CBD wholly appears 2.5 meters deep, is almost vertical, ca. 3 meters high, and cuts the original slope obliquely to the slope direction.

On the basis of facies and color, the colluvium in Loc. 1 is divided into two parts, the upper and the lower. The lower colluvium consists of bright-yellowish-brown to brown gravelly sand, the texture of which is similar to the weathered bedrock but slightly richer in clay and darker in color. The upper colluvium consists of soft and loose black soil. Although their boundary is gradational, it is fairly sharp for bottom of black soil. The upper colluvium contains obviously less amount of granule and coarse sand than the lower one. At the boundary, therefore, the texture of colluvium changes abruptly accompanied with a sudden change of the color.

The radiocarbon date, 9,460 +60/−50 yr. B.P. (TH-1828), was obtained from the black soil at the base of the upper colluvium.

Loc. 2 (Fig. 3)

Loc. 2 is located on a low-relief area near to hilltop. The CBD is on a small slope which is about 10 meters in height and faces northeast. The slope inclination just

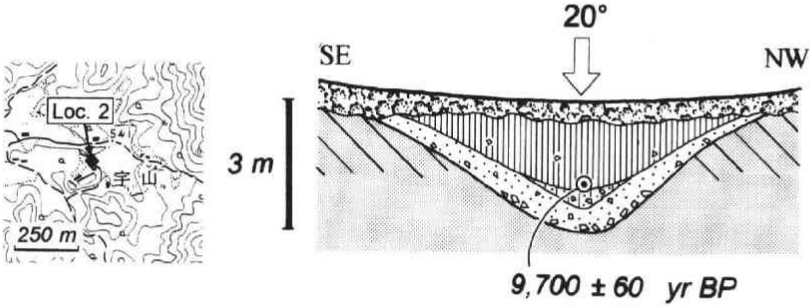

Fig. 3 Topography and a cross section of CBD at Loc. 2

back of the outcrop is about 20° and the ground surface shows slightly depressed feature. The outcrop surface, on which the whole of the CBD appears, is at an angle of 43° and 3.5 meters high. The granitic bedrock is weathered into gravelly sand, in which core stones are scattered. Near the ground surface, the weathered bedrock is tinged with reddish brown. Such color of weathering crust is considered in Japan to indicate severe weathering during the Last Interglacial Stage, and thus implies that the slope had already existed before that time.

On the basis of facies and color, the colluvium in Loc. 2 is divided into three parts ; the upper, the middle, and the lower. Since the lower colluvium consists of bright-yellowish-brown to brown gravelly sand and contains gravel originated from core stones in the bedrock, its appearance is similar to the weathered bedrock. Along the bottom of the lower colluvium, gravel is concentrated. The middle colluvium consists of dark brown loamy sand containing gravel and shows the intermediate facies between the lower and the upper. The upper colluvium consists of soft and loose black soil containing smaller number of smaller-sized gravel than the underlying colluvium. At the base of the upper colluvium, the texture and the color of colluvium change abruptly.

The radiocarbon date, 9,700±60 yr. B.P. (TH-1829), was obtained from the black soil at the base of the upper colluvium.

Loc. 3 (Fig. 4)

Loc. 3 is located at the tail of densely-dissected erosional piedmont gentle slope. The CBD is on a slope which shows a typical topography of zero-order basin, with a north aspect, at about 50 meters in distance and about 20 meters in relative height from the divide. The slope inclination of the depression axis is about 15° immediately back of outcrop, and that of the surrounding slope is 25° to 30°. The outcrop surface is at an angle of 50° and faces wide valley floor. The bedrock exposed there consists of interbedded unconsolidated sandstone, siltstone, and mudstone of the Bihoku Group.

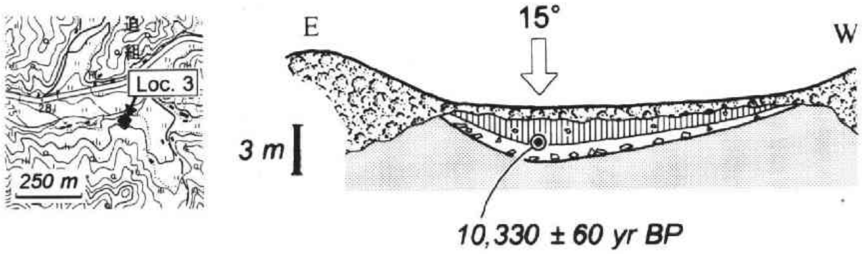

Fig. 4 Topography and a cross section of CBD at Loc. 3

The bedrock cannot yield gravel because of its friability, whereas the colluvium contains gravel. This gravel is interpreted to be derived from the upstream of the zero-order basin where conglomerate of the Bihoku Group is distributed. The colluvium in Loc. 3 is divided into two parts, the upper and the lower. The lower colluvium consists of yellowish brown loam which contains gravel, maximum diameter 30 centimeters, mainly 1 to 3 centimeters. The gravel is concentrated along the base of colluvium. The upper colluvium consists of black soil containing a small amount of gravel. The color and the texture of colluvium change abruptly at the boundary between the lower and the upper colluvia.

The radiocarbon date, 10,330±60 yr. B.P. (TH-1830), was obtained from the black soil at the base of the upper colluvium.

Loc. 4 (Fig. 5)

Loc. 4 is located on low-relief hilly landform near to hilltop with 30 to 50 meters in relative height. The CBD is on a southwest-facing slope expressing zero-order basin topography, about 50 meters apart and about 30 meters low from a divide. The slope inclination immediately back of the outcrop is about 20° in the depression. The outcrop surface is at an angle of 47°. The bedrock, granite porphyry, is highly weathered.

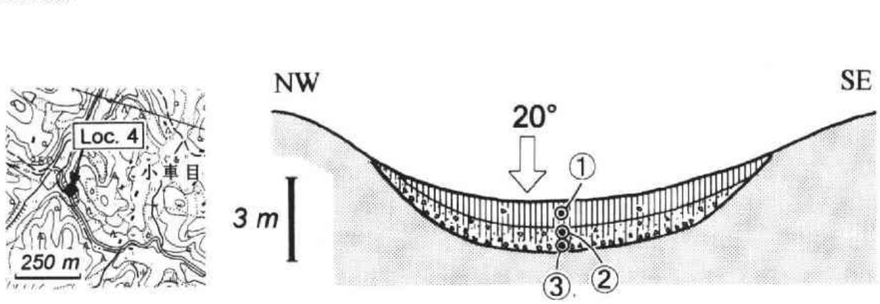

Fig. 5 Topography and a cross section of CBD at Loc. 4
Volcanic grass shards derived from the K-Ah tephra (6.3 ka) are found only in the sample ①, middle part of the upper colluvium.

The colluvium in Loc. 4 is divided into two parts, although the boundary is relatively unclear in comparison with the above-mentioned three CBDs. The lower colluvium consists of dark brown to brownish black compact gravelly sand, which contains a large quantity of granule originated from phenocrysts in weathered granite porphyry. The basal part comprises mainly granule. The upper colluvium consists of loose black soil, in which a small number of granule is scattered.

No sample for radiocarbon dating could be taken from Loc. 4, because living roots penetrate into the whole strata of colluvium. Basal age was therefore estimated tephrochronologically by difference in volcanic glass shards contained in the colluvium. Around Loc. 4, the following three tephras are available for tephrochronology ; the SI tephra of 38 ka (Kanauchi and Sugihara, 1994) and about 40 centimeters thick ; the AT tephra of 24-25 ka (Ikeda *et al*., 1995) and about 30 centimeters thick ; and the K-Ah tephra of 6.3 ka (Machida, 1991) and about 10 centimeters thick, although the K-Ah layer is rarely observed in field due to alteration to black soil. While the SI contains volcanic glass shards of pumice-type but no bubble-wall-type (bw-type), both the AT and the K-Ah comprise mainly the bw-type. The latter, however, differs in color of the glass shards ; that is, all the AT glass shards are colorless, whereas the K-Ah contains a small quantity of brown-colored glass shards mingled with a large number of colorless ones.

The three horizons (①~③ in Fig. 5) contain the bw-type glass shards ; but the brown-colored shards are found only in the middle part of the upper colluvium (①). This indicates that the proper horizon of the K-Ah lies between ① and ② ; that is, in the middle or lower part of the upper colluvium.

Distribution of the SUP tephra, ca. 16 ka, is restricted to the northern half of the study area, while Loc. 4 is situated in the southern half. Although the stratigraphic relationship between the SUP and the colluvium of Loc. 4 cannot be confirmed directly, the following two facts suggest that the accumulation in Loc. 4 started after the fall of SUP : one, the colluvium of Loc. 4 is tinged with dark brown color even near to the base, and, two, such-colored soil is not found below the SUP layer where SUP is distributed. It is concluded that the inception of accumulation in Loc. 4 occurred in the age between ca. 16 ka and 6.3 ka.

4. Discussion

4.1. Inception age of accumulation in CBD

The soil for each radiocarbon dating at Locs. 1, 2, and 3 was sampled from the horizon at the base of the upper colluvium : There exists the lower colluvium beneath the horizon. In addition, the radiocarbon date from black soil designates not the age of colluvium deposition but the age of humus accumulation, in the strict sense. It is therefore conceivable that the date of each sample indicates only the age of change in environment for soil formation, such as climatic or vegetational change.

However, the lower colluvium is certainly the first fill of the bedrock depression and consists of coarse material, which has similar texture to the underlying weathered or unconsolidated bedrock. Moreover, the soil color and the texture of colluvium change abruptly and simultaneously. These characteristics of colluvium suggest that the lower colluvium was supplied from the exposed bedrock on the surrounding slopes within a short period immediately after the last erosion processes such as gullying or landsliding occurred there, and that the inception of black soil accumulation in the bedrock depressions is caused by stabilization of ground surface after the subduing and revegetation of surrounding slopes. In short, the date obtained from the black soil at the base of the upper colluvium can be regarded as the inception age of accumulation in the CBD.

4.2. Correspondence of the inception ages of accumulation

The radiocarbon dates designating the inception ages of accumulation in the CBDs are 9,460 $+60/-50$ (Loc. 1), 9,700$\pm$60 (Loc. 2), and 10,330$\pm$60 yr. B.P. (Loc. 3), clustering around 10 ka. Taking account of that the all samples for dating are black soil, the clustering of three ages can be interpreted as the coincidence in ca. 10 ka. As for Loc. 4, the tephrochronological information on the inception age of accumulation is consistent with the age, ca. 10 ka.

The simultaneity that accumulation in all of three (or three out of four, at least) CBDs started in ca. 10 ka suggests that the inception of accumulation was not brought about by individual condition in each CBD but reflected a certain common cause prevailing over the study area. The presence of the colluvium dated ca. 10 ka shows that no excavating processes such as gullying or landsliding occurred for the last 10,000 years in the CBDs, where such processes could occur in or until ca. 10 ka ; in other words, the CBDs were already fossilized as erosion landforms in ca. 10 ka. Therefore, the environment in ca. 10 ka is estimated to have been suitable for erosion processes on the upper part of hillslopes in comparison with the environment in the period succeeding to ca. 10,000 years.

4.3. Paleoenvironment around 10 ka

The cross-section and the topographic position of the CBDs indicate that the depression feature shown by the base of colluvium has been produced by the same geomorphic processes as those prevailed in present valley heads ; i.e. by gully erosion or small-scale landslide. The fossilization age of the CBDs, ca. 10 ka, corresponds to the the Pleistocene-Holocene boundary, a time of known significant climatic change. For CBDs, the formation as bedrock depressions and the succeeding fossilization should have been influenced by the change of hydrogeomorphological environment ; to be concrete, strongly influenced by the change of precipitation condition rather than the change of temperature.

A lot of reports on pollen analysis have proved that the climate in the Japanese Islands turned to humid in the period from the end of the Pleistocene to the beginning of the Holocene. I have, however, never read any reports concluding that the period around 10 ka was the most humid in the last 10,000 years. It is therefore possible that the CBDs in this study have resulted from not the climatic change affecting the whole of the Japanese Islands around the Pleistocene-Holocene boundary but only a local and episodic event at ca. 10 ka, such as an earthquake. But, I would rather infer that the CBDs in the study area reflect the humid climate around 10 ka. In my investigations on hillslope development of valley-head areas in Hokkaido (Yoshiki, 1995) and Northeastern Honshu (Yoshiki, 1993), channel heads in the past have already existed at the almost same location as the present ones by ca. 8 ka at the latest. The locations of channel heads are considered to be controlled by the climatic humidity (Montgomery and Dietrich, 1988), so that the results of my investigations in other areas suggest that the climate of the Japanese Islands in the beginning of the Holocene was humid as same as that in the succeeding period up to present. Therefore, it is likely that the CBDs in this study also have resulted from the humid climate around 10 ka, although the erosion processes forming bedrock depressions were probably caused by a heavy rain which was exceptional for even in that time.

More definite and more concrete hydrogeomorphological environment in ca. 10 ka will become clear in future, according to the confirming presence of CBDs formed in the same age in other regions and the chronological studies on the landforms whose development immediately reflects a change of rainfall condition as well as channel heads and the bedrock-depression heads on hillslopes.

5. Conclusions

Radiocarbon dating and tephrochronology for colluvium suggested that four CBDs on hillslopes in the northern part of Hiroshima Prefecture have formed simultaneously in ca. 10 ka, the Pleistocene-Holocene boundary, and that they have been fossilized as erosion landforms since that time.

Correspondence of the ages when accumulation started in the CBDs shows that the CBDs have formed as a result of some environmental change prevailing over the study area, and indicates that the environment in ca. 10 ka was more suitable for erosion by gullies and landslides on the upper part of hillslopes than that in the whole period from ca. 10 ka to present. Although such environment probably designates rainfall character affecting channel development, the chronology of CBDs in a region cannot suggest more concrete hydrogeomorphological environment in that time. But still, it is very likely that the gullying and landsliding on hillslopes of the study area in ca. 10 ka could occur at the almost same location as present, and that the climate was already humid enough to cause gullying and landsliding there.

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